Ares I-X Thermal Model Correlation and Lessons Learned

Ruth M. Amundsen
NASA Langley Research Center

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Outline

Background

VAB Testing

Day of Flight Natural Environments

Model Correlation to On-pad/Flight for OFI

Aeroheating environment

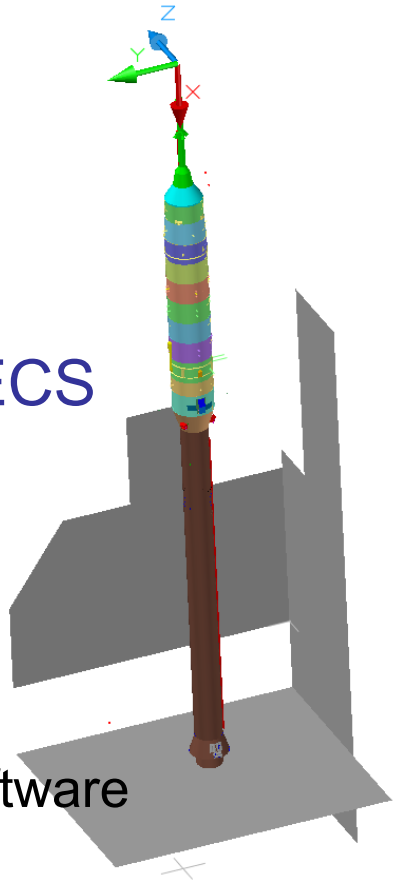
Model Correlation to Flight for DFI

Lessons Learned/Best Practices

Summary

Thermal Background

- Ares I-X Thermal Control
  - Passive Thermal Control
    - White paint
    - Thermal grease
    - Limit avionics powered-on time
  - Active Thermal Control
    - ECS (disconnect at T-4 hours)
    - Fans
- Atlas-heritage avionics never flown without T-0 ECS
  - Many early trade studies looking at thermal options
- Ares I-X full vehicle thermal model
  - In Thermal Desktop®
  - IPT submodels from CM/LAS, Avionics, USS, RoCS
  - FS portion developed at LaRC - ATK used different software



VAB Testing

- Thermal testing done in the VAB in Sept & Oct 2009
  - Verify fan operation and effectiveness
    - Potential 8 hours on-pad without ECS
    - Large thermal mass of air volumes allows fan effectiveness
  - Verify thermal grease effectiveness
  - Correlate thermal model
- Initial Vehicle Power Application (IVPA) September 2009
  - First power-up of avionics in full vehicle
- Thermal Excursion Test (TET) October 2009
  - Disconnect of ECS while avionics powered, to test fan cooling
- Both tests used for thermal model correlation
- All avionics components stayed well under limits
  - Thermal grease very effective
  - Fans highly successful in cooling components

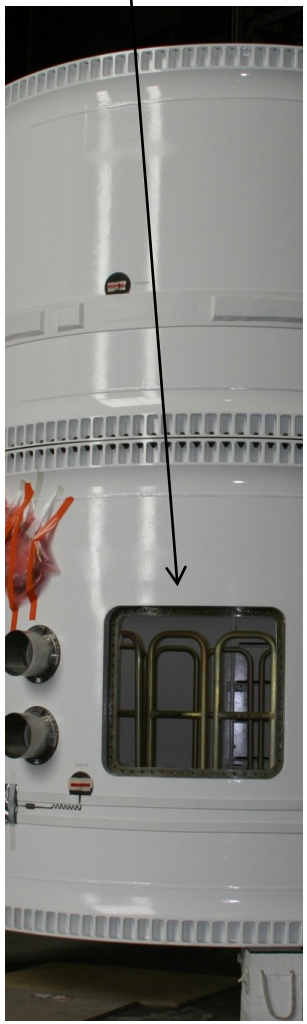
Model Correlation to VAB Testing

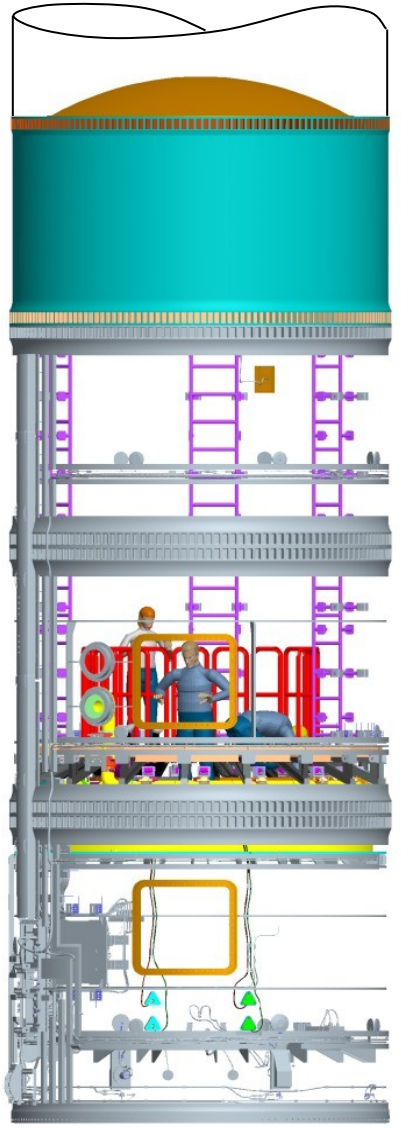
- Main actions in correlating model
  - Input actual box power timeline
  - Added measured ambient temperatures and purges
  - Corrected RRGU mounting (non-flight for IVPA)
  - Decreased avionics box dissipated powers
  - Increased thermal grease effective contact value
    - Final values: 27 to 104 Btu/hr-ft^2-°F (large & small boxes)
  - Good agreement of convective coefficients (CFD/TD/data)
    - Values: 2-3 Btu/hr-ft^2-°F for fan-only
  - ~20 runs of each case
- Final model correlation: RMS error of 2.7°F (1.5°C) on peak temperature averaged over all avionics boxes
- Gary Holmstead, Avionics thermal lead, was responsible for the avionics model and instrumental in correlation

First Stage Avionics Module (FSAM)

FSAM being lowered into XL

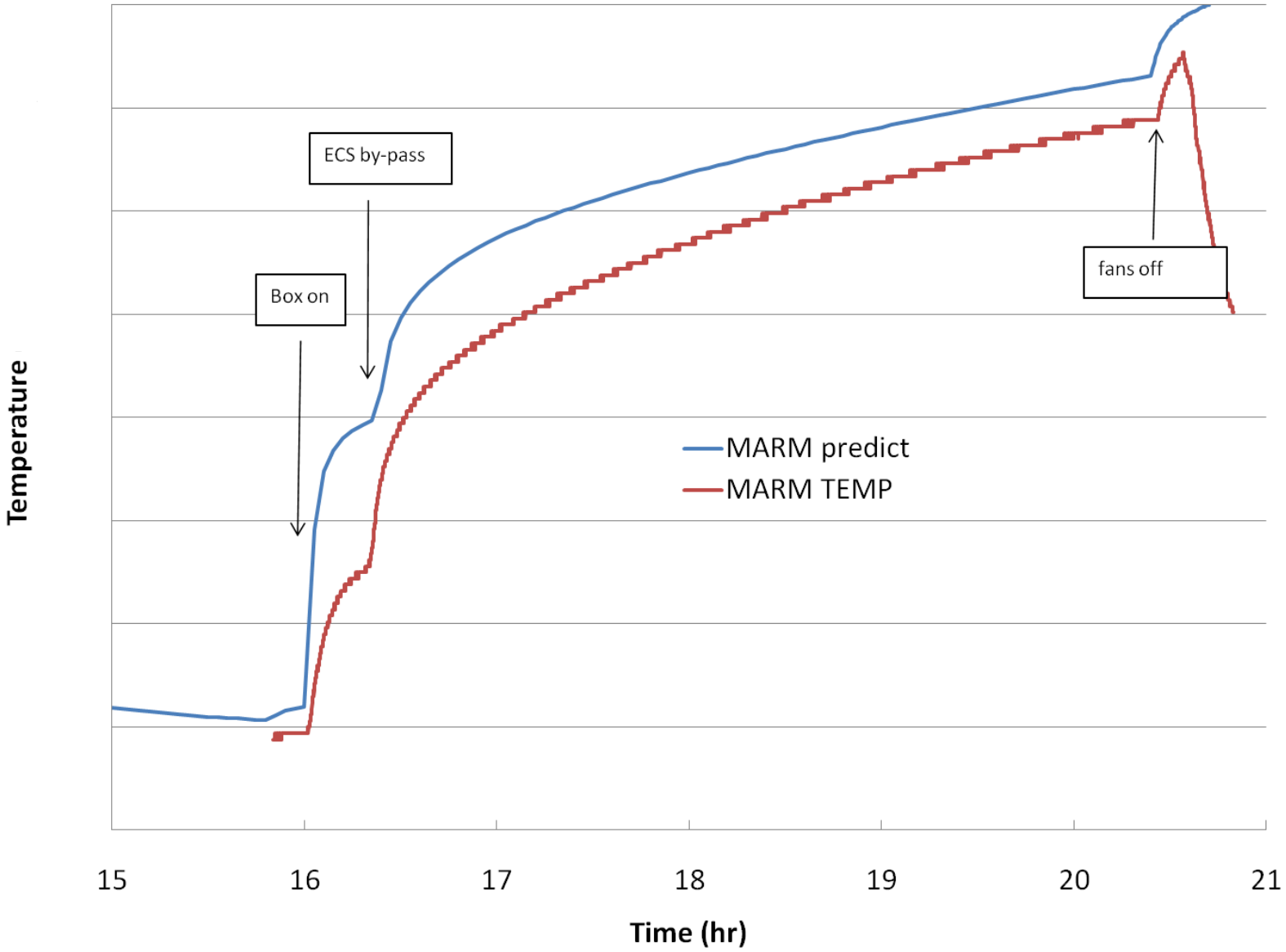
FSAM access



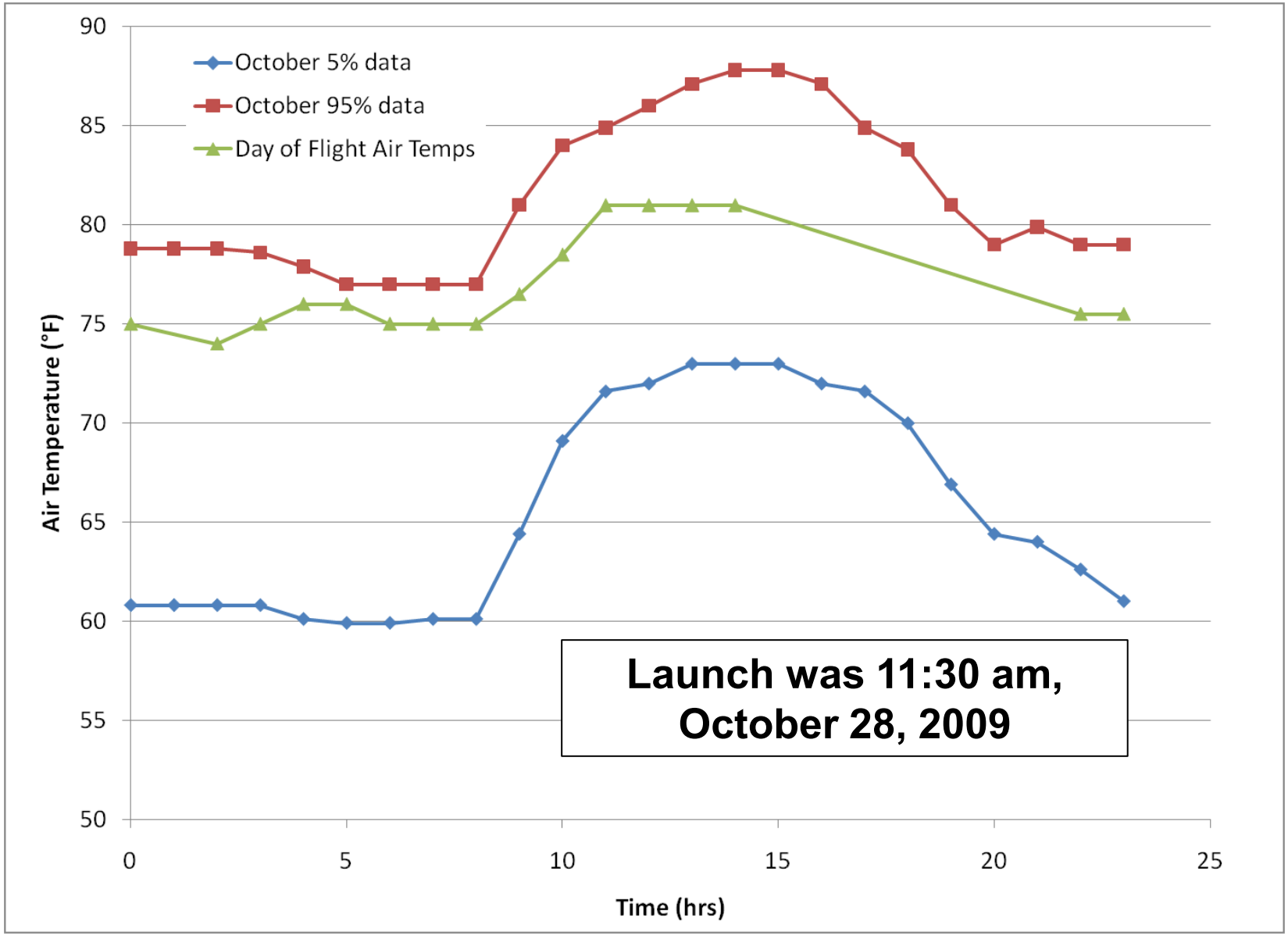


- FSAM ECS multiple high-velocity ports
  - Fans had little effect when ECS on
- ~400 lb XL air provides thermal stability when ECS off

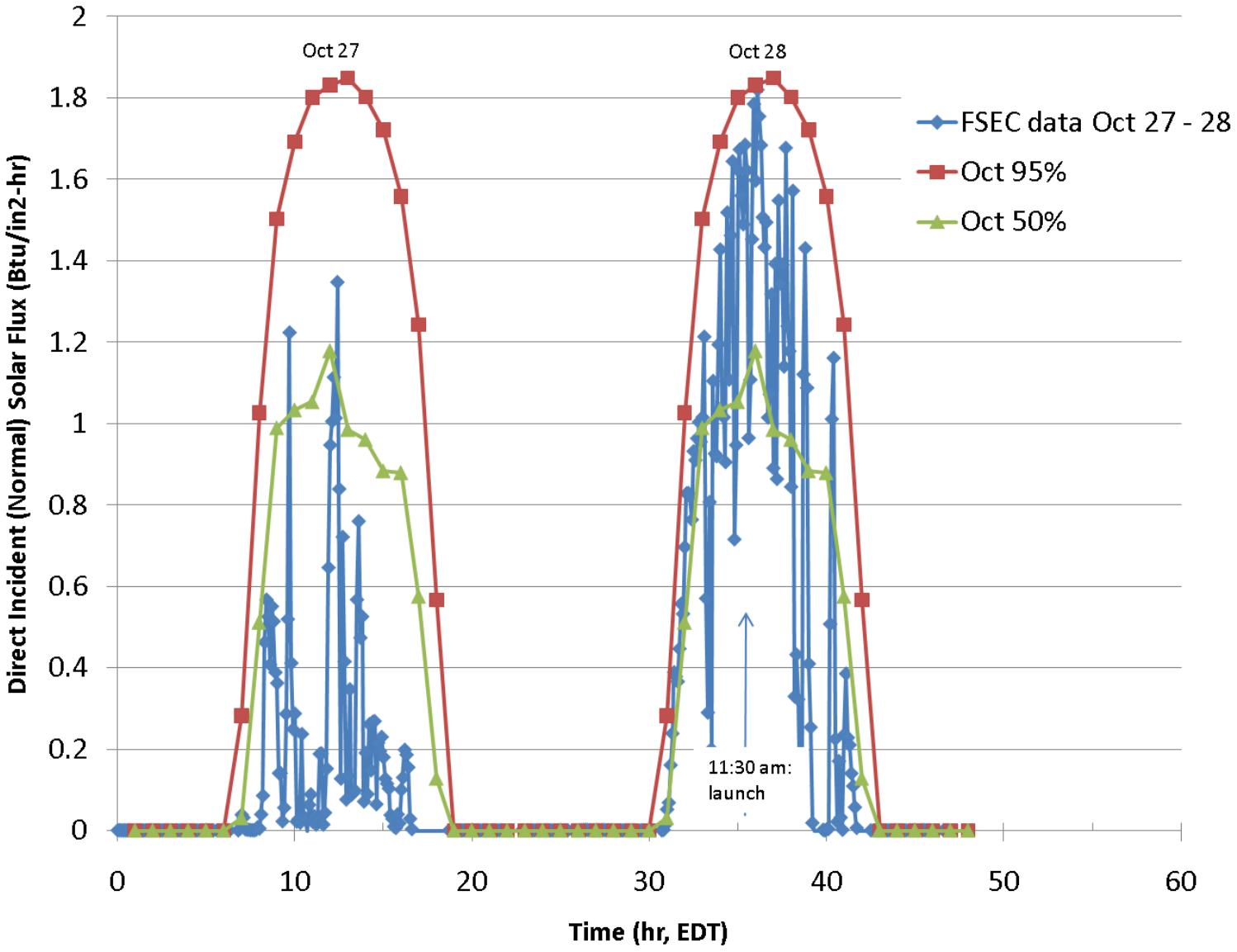
Correlation to TET in VAB: MARM



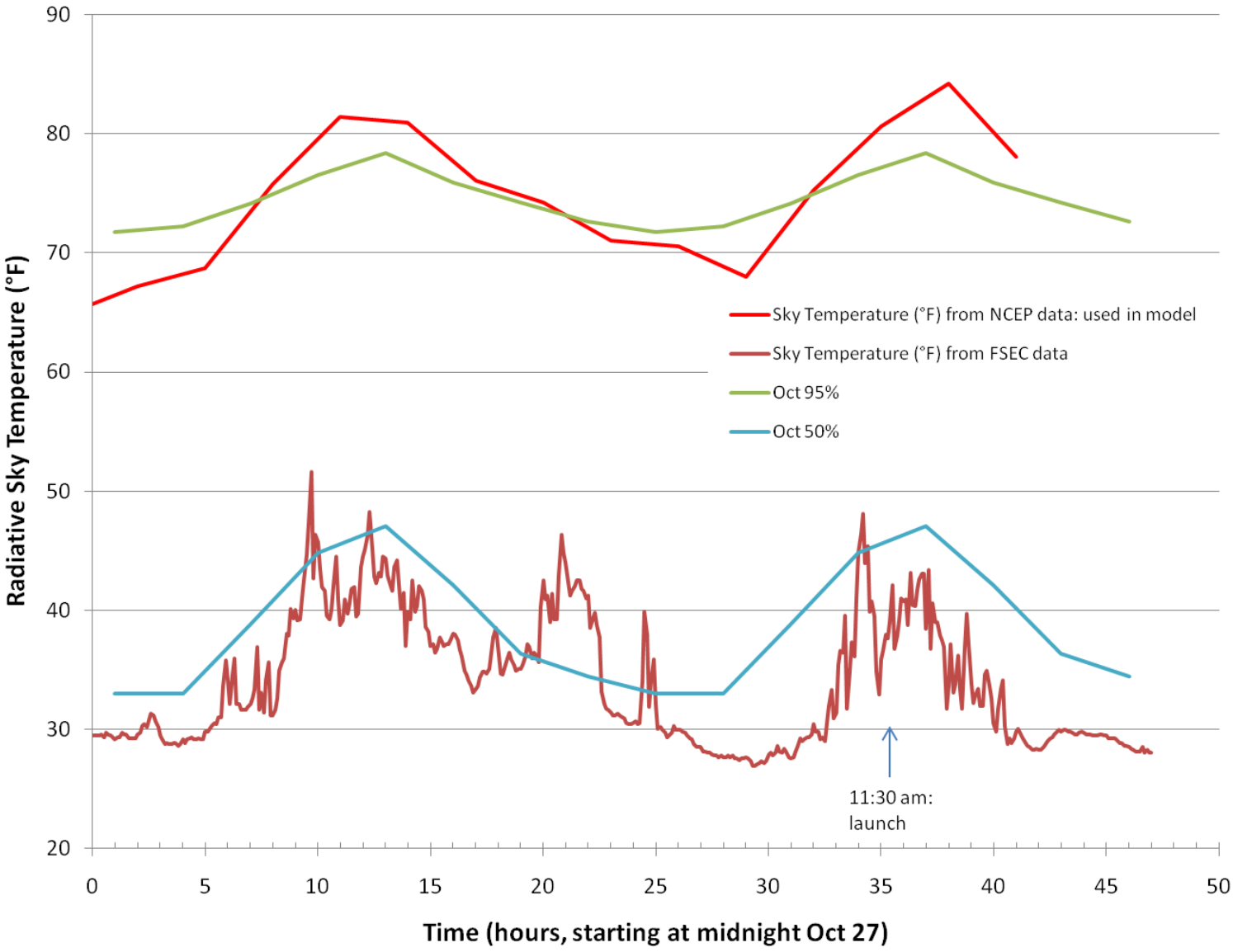
Air Temperature - Day of Flight



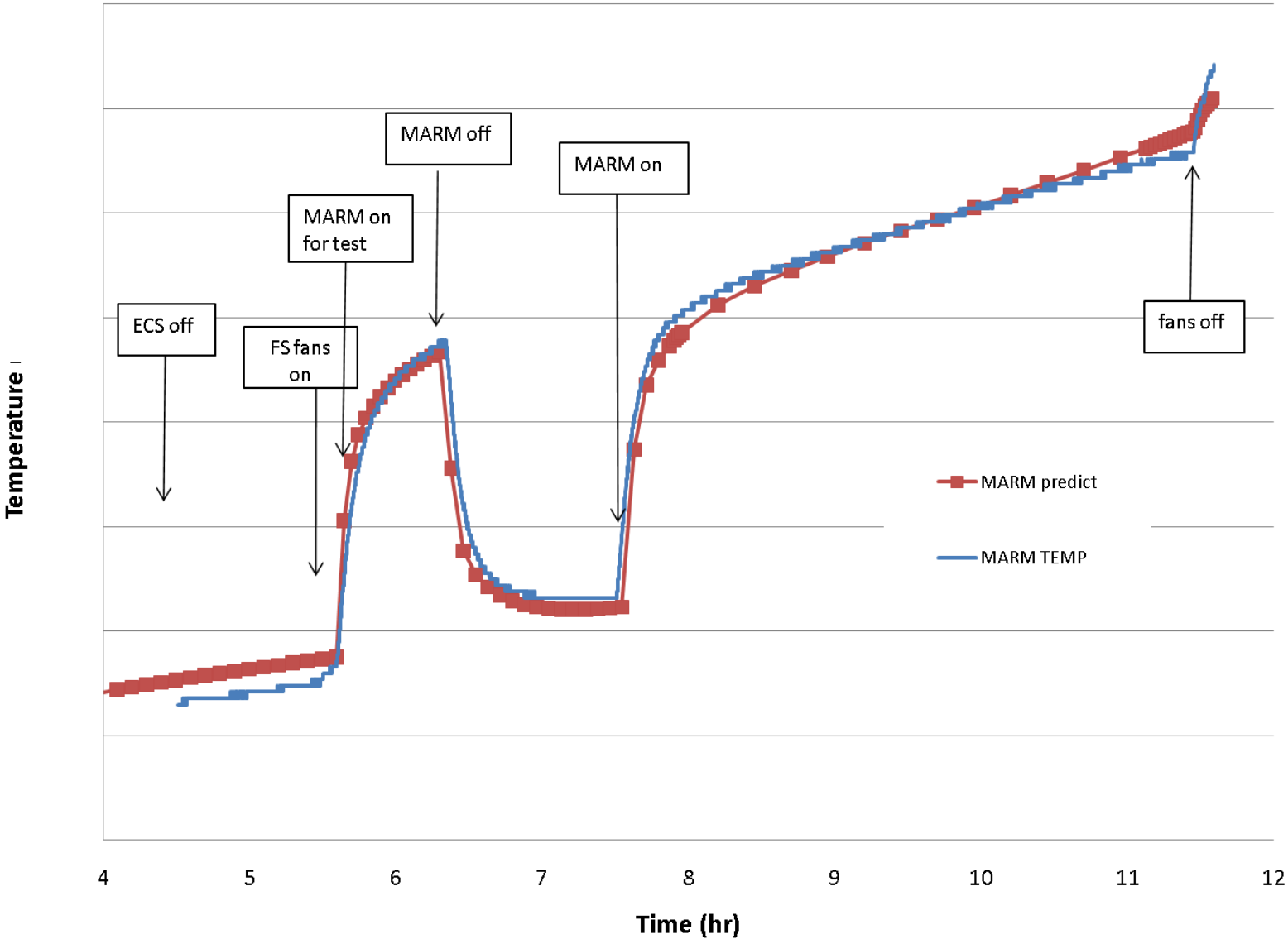
Day of Flight - Direct incident solar flux



Day of Flight - Sky radiative temperature



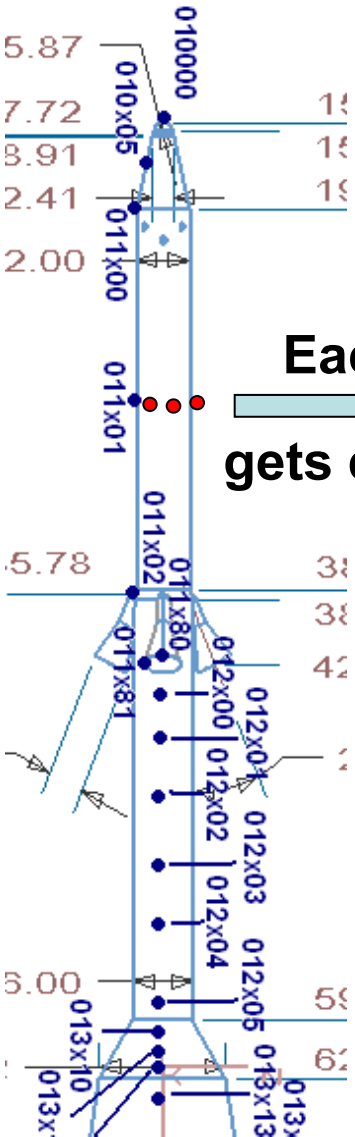
Correlation to Flight OFI: MARM



Applying Aeroheating to Thermal Model

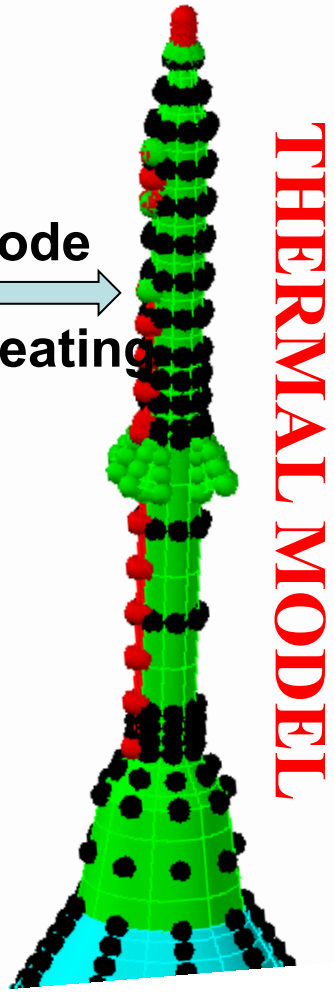
- MINIVER heating at discrete body points used

BODY POINT MAP



Each thermal node

gets closest BP heating



THERMAL MODEL

Every body point has a time & temperature dependent heating file that must be converted to heat flux

BP	Time	Alt	hc (OF)	hc (760F)	hc (2000F)	Hrec	Hwall (OF)
	sec	ft	lbm/ft2-s	lbm/ft2-s	lbm/ft2-s	Btu/lbm	Btu/lbm
X10000	0.00	0.00	0.155E-02	0.158E-02	124.5	299.8	634.8
X10000	5.00	235.04	0.150E-01	0.145E-01	124.5	299.8	634.8
X10000	10.00	1059.19	0.219E-01	0.212E-01	124.7	299.8	634.8
X10000	15.00	2556.14	0.274E-01	0.265E-01	125.1	299.8	634.8
X10000	20.00	4771.66	0.322E-01	0.311E-01	126.0	299.8	634.8
X10000	25.00	7748.66	0.365E-01	0.352E-01	127.7	299.8	634.8
X10000	30.00	11429.73	0.394E-01	0.381E-01	129.5	299.8	634.8
X10000	35.00	15722.98	0.415E-01	0.400E-01	131.5	299.8	634.8
X10000	40.00	20537.59	0.430E-01	0.415E-01	133.9	297.4	634.8
X10000	41.00	21554.94	0.432E-01	0.417E-01	134.5	297.4	634.8
X10000	42.00	22589.04	0.434E-01	0.419E-01	135.0	297.4	634.8
X10000	43.00	23639.38	0.435E-01	0.420E-01	135.6	297.4	634.8
X10000	44.00	24705.44	0.437E-01	0.422E-01	136.3	297.4	634.8
X10000	45.00	25786.69	0.438E-01	0.422E-01	136.8	297.4	634.8
X10000	46.00	26882.64	0.439E-01	0.423E-01	137.5	297.4	634.8
X10000	47.00	27992.76	0.440E-01	0.425E-01	138.4	297.4	634.8
X10000	48.00	29116.38	0.440E-01	0.424E-01	138.9	297.4	634.8
X10000	49.00	30252.63	0.439E-01	0.424E-01	139.5	297.4	634.8
X10000	50.00	31400.50	0.439E-01	0.424E-01	140.3	297.4	634.8
X10000	51.00	32559.13	0.439E-01	0.424E-01	141.1	297.4	634.8
X10000	52.00	33728.04	0.439E-01	0.424E-01	142.1	297.4	634.8
X10000	53.00	34907.16	0.440E-01	0.424E-01	143.3	297.4	634.8

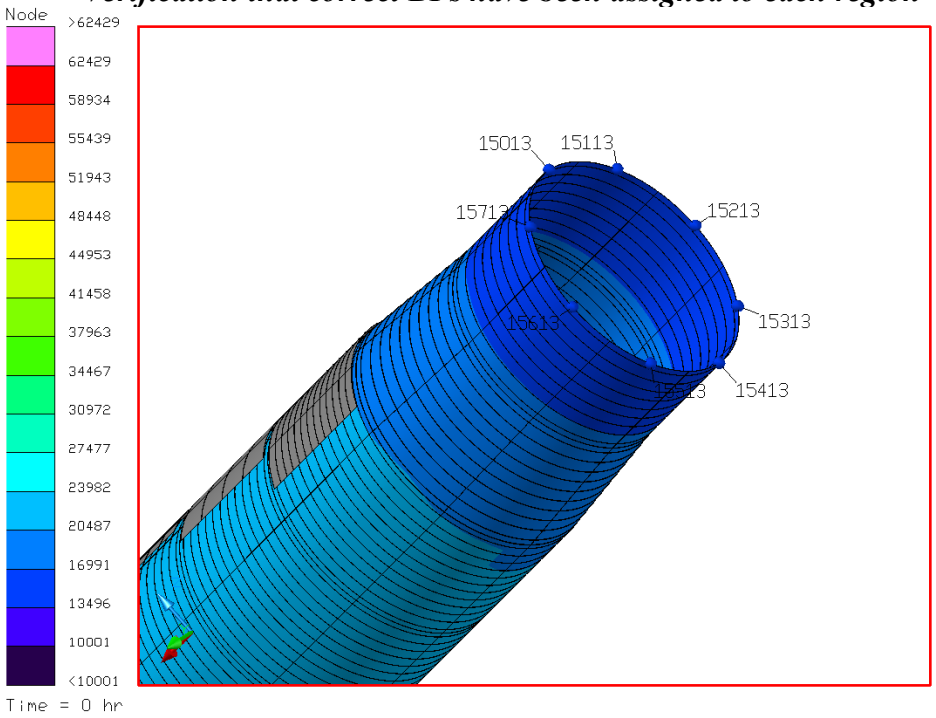
Converted heat flux applied to each node and interpolated in time and node temperature

BPMapper

- Latest 5.3 version features:
  - All graphical (GUI) interface
  - Single external array file, faster run time (x10)
  - Graphical display of cold wall heating
  - No model node number restrictions

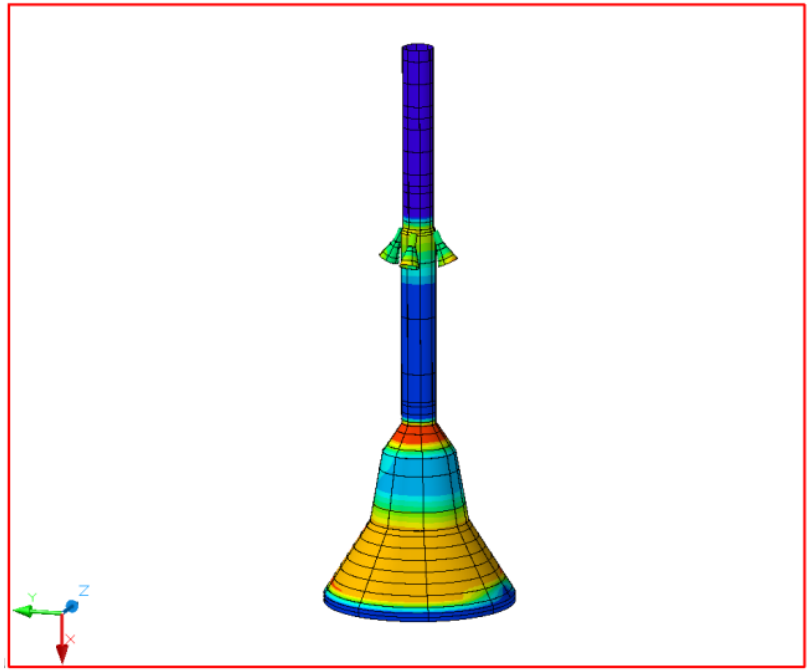
Visual Verification of BP-Node Mapping

Verification that correct BPs have been assigned to each region

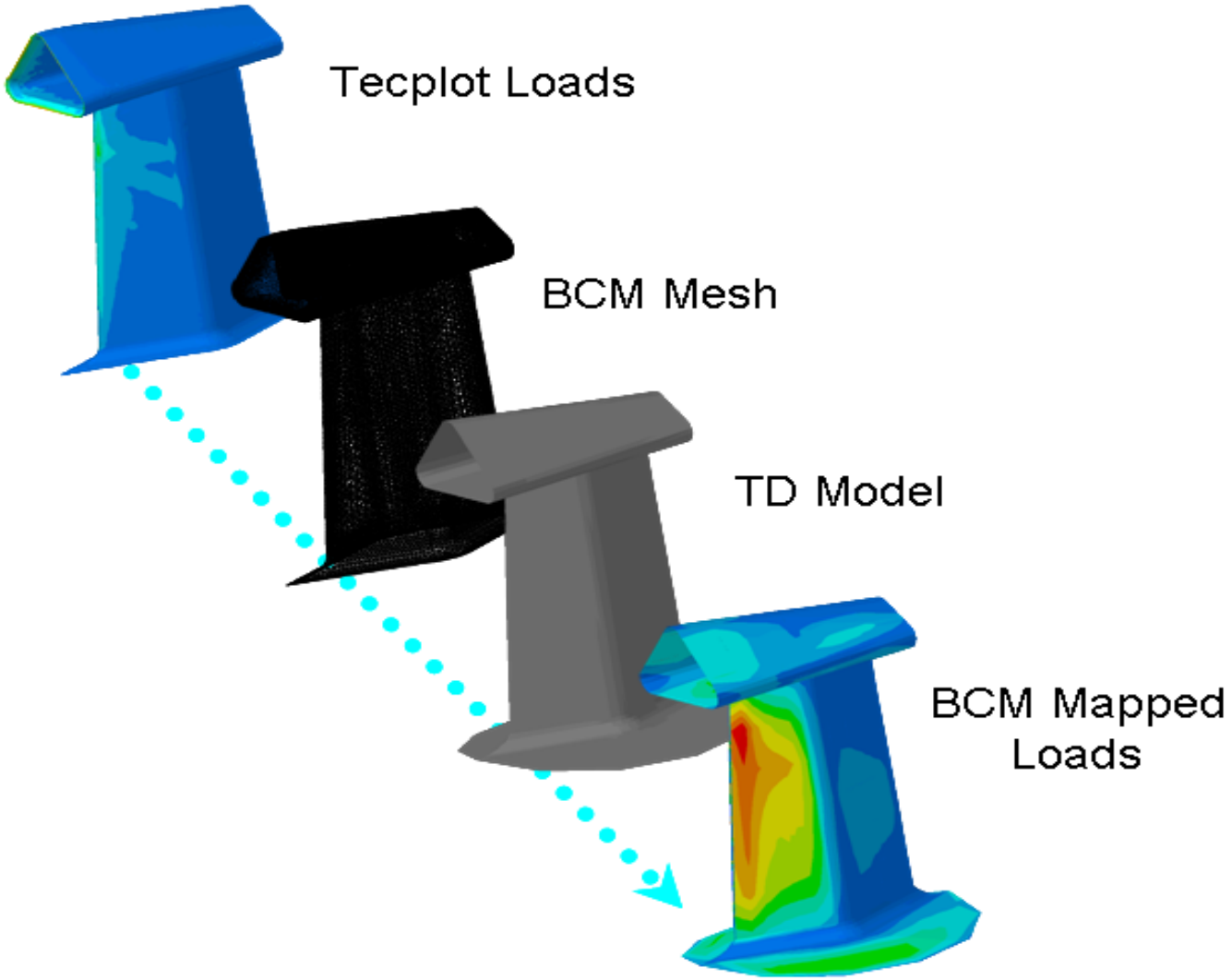


Visual Verification of Aeroheating Fluxes

Verification that correct aeroheating applied in each region; can be viewed as transient animation to verify changes during flight



Aeroheating Application using TD BCM



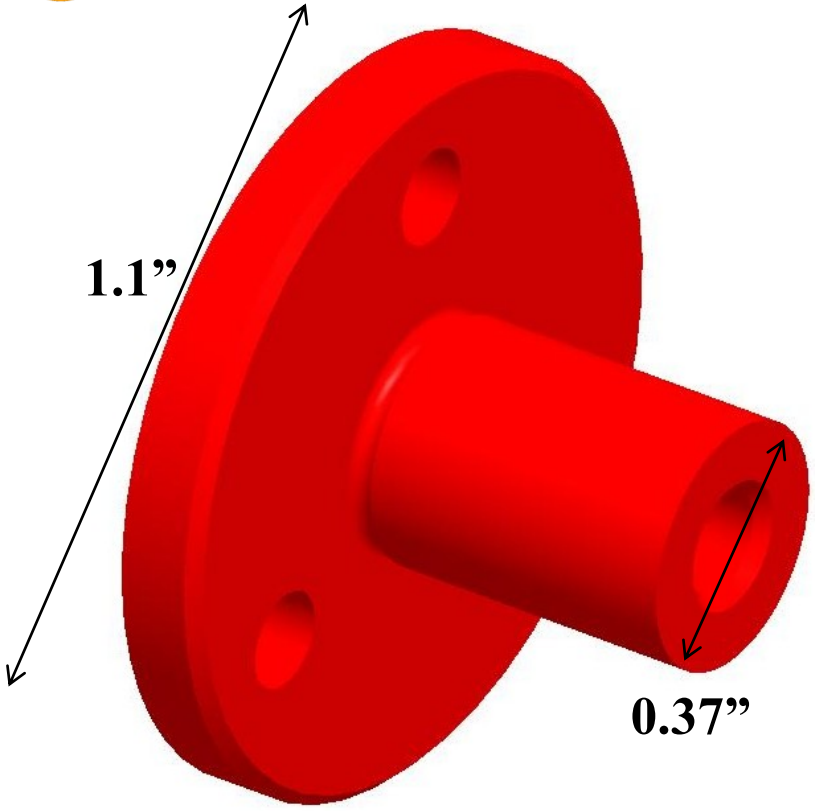
BCM Aeroheating Application

- Post-flight, Boundary Condition Mapper (BCM) method in Thermal Desktop evaluated for entire vehicle
  - Dense CFD mesh (USM3D), coarse timeline
  - Much simpler application
  - TecPlot files converted to BCM input format using Map2CFD code
  - Currently, correlation using USM3D not as good as MINIVER (USM3D not validated for heating)

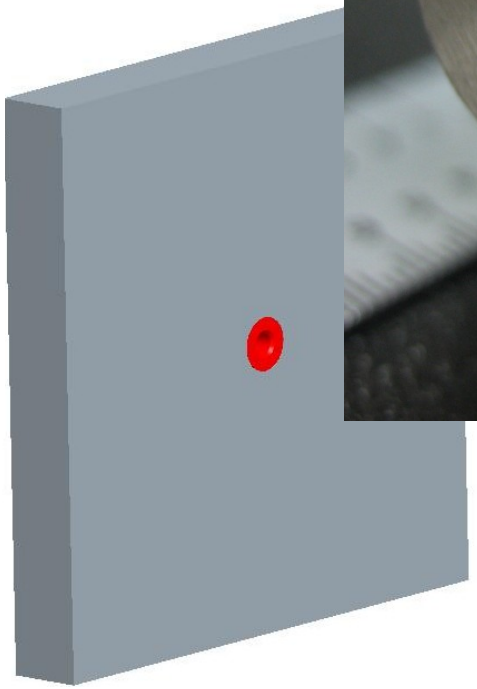
Model Correlation to DFI

- CM/LAS sensors embedded: matched skin temperature
- Many IS, USS and FS sensors were TCs in calorimeters
  - TC is light and not well-connected to skin (phenolic isolator)
  - Responds immediately to heat flux instead of tracking skin temp
- “Glue-on” FS TCs responded faster than skin
- Lesson learned: if you want decent skin temperature measurements, embed them in the skin
- All sensors added to model from DFI spreadsheet
  - New ‘Measures’ feature in Thermal Desktop® allowed import of sensor location spreadsheet
  - Entire DFI list imported in a single stroke
  - Calorimeter, skin and embedded TCs handled differently
- In correlation, no changes made to basic thermal model
  - Updates to aeroheating loads
  - Changes to heating body point mapping
  - Revision of sensor mass/contact

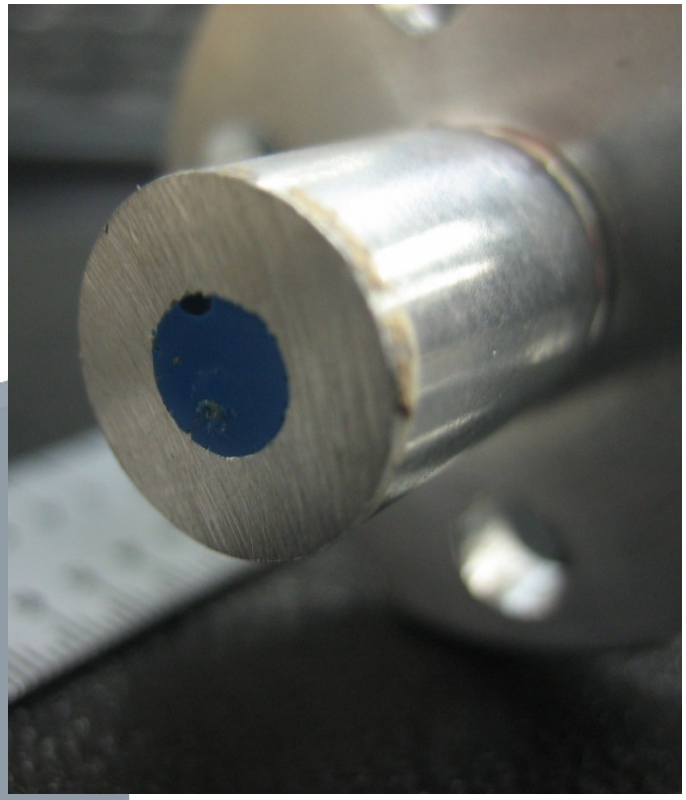
CM/LAS Embedded Skin TCs



TC plug



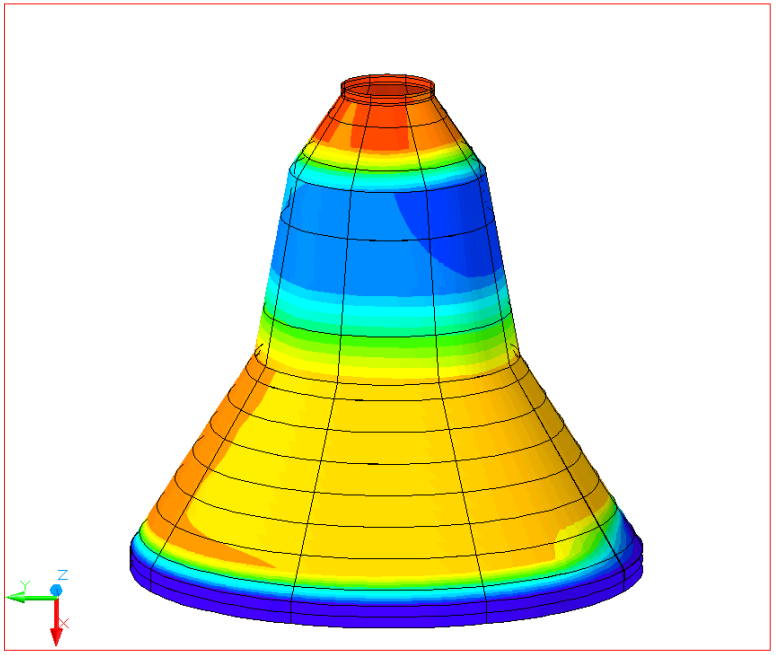
TC plug installed



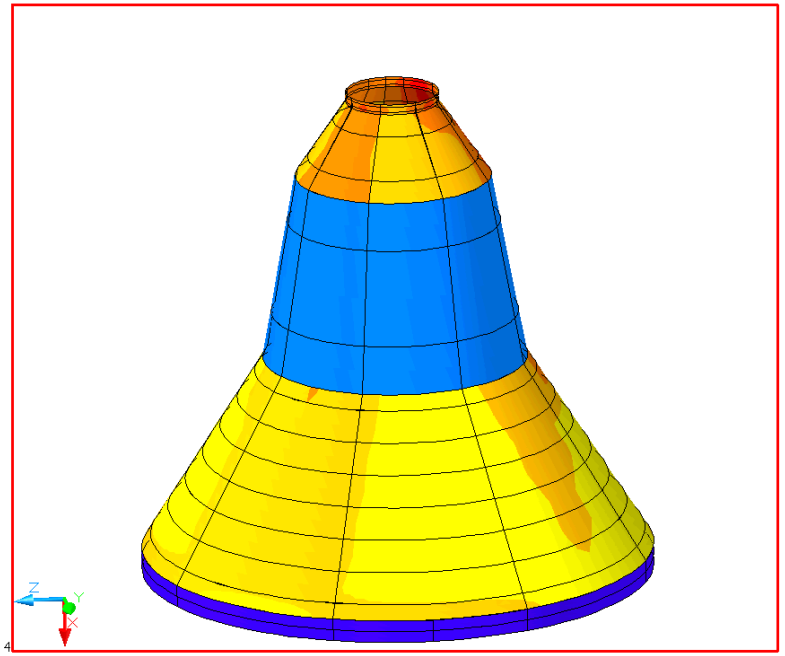
TC within plug

Aeroheating Mapping Corrections

- Initial mapping of CM/LAS allowed aeroheating flux to “seep” across angle changes
- Corrected mapping brought CM/LAS model predictions into agreement with flight DFI data



Original mapping

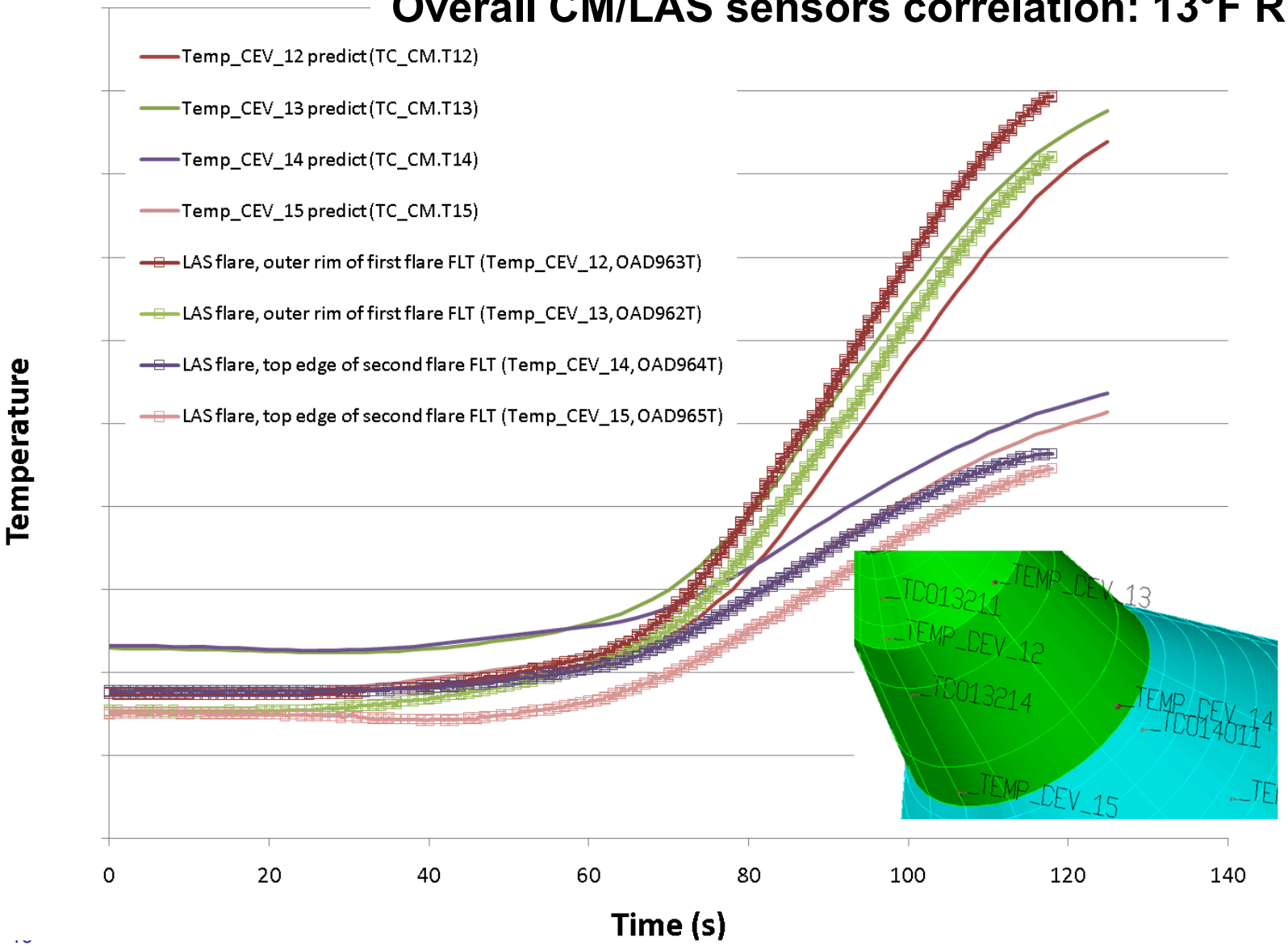


Corrected mapping

Aeroheating flux (Btu/hr-ft^2)

CM/LAS DFI - Party hat

Overall CM/LAS sensors correlation: 13°F RMS



Thermal Modeling Best Practices

- Define model standards and guidelines
  - Number and naming of submodels, layers, radiation groups, case sets
  - Units
  - Materials
  - Symbols and symbol groups
  - Common co-ordinate system
  - Comments
  - Use of boxes
  - Consolidate contactors/conductors/ties
  - Write out calculation expressions
  - Notes section for model documentation
- For model integration:
  - Pre-coordinate above using template file
  - Enforce model quality and delivery timelines

Thermal Modeling Best Practices - 2

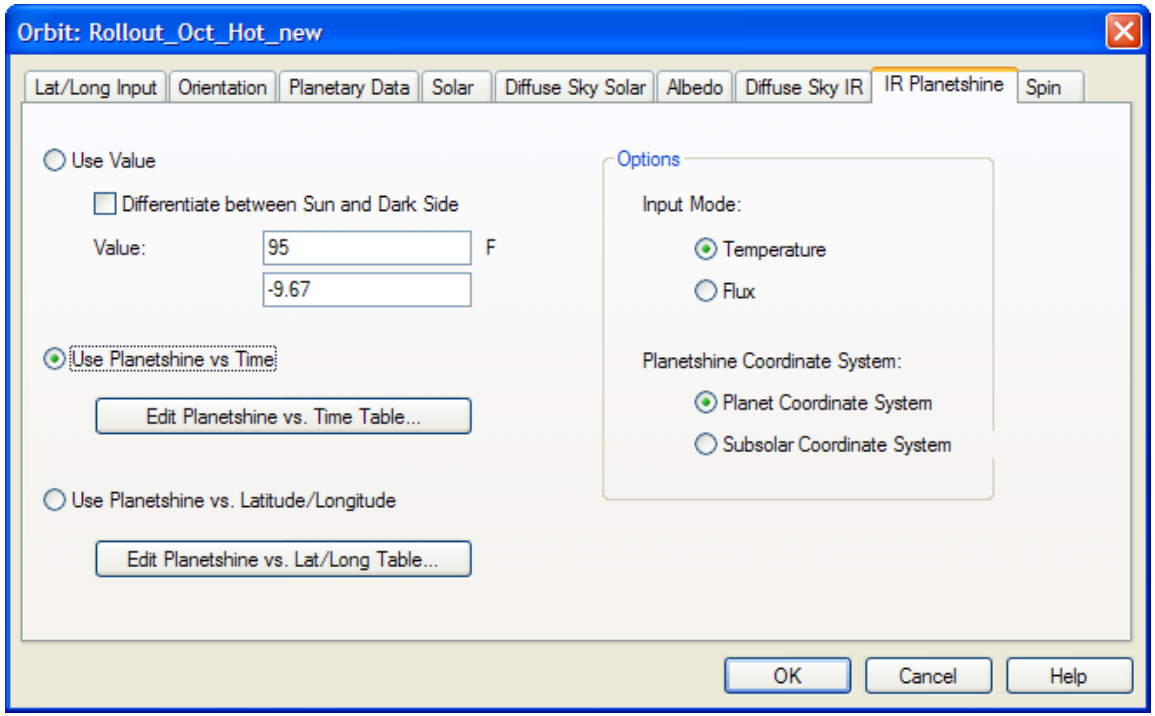
- Use well-defined, documented method for checking submitted models and integrating into vehicle model
- Maximize use of symbols and Logic Manager blocks
- Ensure all cases captured in initial logic definition
  - Hot, cold, nominal, max gradient, day of launch, day prior to launch
- Restart cases using previous run, including both thermal nodes and fluid lumps
- Ensure common software and complier version among all modelers
- Avoid external code in lieu of Thermal Desktop functions
- Maintain a spreadsheet of all model variables, when they were changed and why, and all case runs

Thermal Modeling Best Practices - 3

- Plan and standardize solar and planetary flux calculation
  - Sky temperature and diffuse solar levels are drivers in on-ground thermal predictions
    - Define carefully and in realistic combinations
- Plan and standardize aeroheating flux application
  - Minimum manual work and fewest model restrictions
  - Ensure mesh density corresponds to heating gradients
  - Graphically verify aeroheating mapped to model
  - Heating on full mesh preferable to discrete body points
- Include all engine plumes, including the aero effect on their shape and intensity, using realistic firing timeline
- CFD useful to validate convective coefficients determined within Thermal Desktop
- In flight correlation, use real data for pre-flight cases to define start temperatures

Thermal Desktop Planet Surface Option

- Post-flight, tested TD 5.3 new planet surface option
  - Much easier to use than old method of 'building' the planet
  - All temperatures within 1°F of old method
  - Currently, no input planet emissivity; planet flux must be corrected by $T_{effective} = \left(\varepsilon * T_{gnd}{}^4 + (1-\varepsilon) * T_{sky}{}^4\right)^{0.25}$



Thermal Lessons Learned

- Ares I-X USS developed database of white paints for solar flux mitigation
  - Use solar air mass 1.5 for solar absorbtance (α) values on Earth surface (different solar spectrum than in space changes α)
  - Application process will change α (thicker paint = lower α)
- For avionics box contacts, use thermal grease to improve contact
  - 27 to 104 Btu/hr-ft^2-°F times box contact area for contact conductance
- Fans are effective, but have substantial EMI/EMC and line noise issues that must be addressed early on
  - Also consider voltage drop in lowering fan speed
- Define nominal (measured) avionics powers rather than using maximum specified powers
  - Measure avionics powers during early development
- For correlation, have powered-on heating period and unpowered cooldown period with box temperatures monitored
- Ensure that every item with critical limit has thermal sensor
- Explain purpose of thermal test to management and technicians
- For reasonable skin temperature measurement during aeroheating, sensors must be integrally embedded in skin

Thermal/Management Lessons Learned

- Have contamination (cleanliness and humidity), ECS and venting leads assigned early, separate from thermal lead, integrated into project structure, maintained over entire life of the project
- Set and enforce schedule and quality standards for thermal model products delivered from IPTs to SE&I
- Maintain a Thermal Working Group for the life of the project, including post-flight correlation
- Maintain continuity of personnel in key lead positions
- Simplify management chain for contracts
- Use table-top reviews for disciplines, prior to major reviews
- Carefully scrutinize what is defined as Proprietary
- Defining an aerothermal lead within the direct project structure will allow better control of file formats, configuration control, and schedule

Summary

- All avionics remained within limits during mission
  - Fans were successful in mitigating temperature rise pre-launch, although EMI/EMC was difficult issue
- Single thermal model of entire vehicle, all cases, was very effective in performing thermal analysis
- Thermal model accuracy with respect to avionics was outstanding (3°F)
- Thermal model accuracy for skin DFI during aeroheating was good on CM/LAS (13°F RMS error)
- Calorimeter thermocouples not useful for determining skin temperature
- Many lessons were learned in thermal modeling practices that should be of use to future missions
  - Documented in Ares I-X AIX-TAR-THM0004

Acknowledgments

- The initial methods for applying aeroheating to this model, as well as initial model structure, were supplied by Mark Wall of MSFC
- Thanks to John Sharp, Frank Leahy, Ken Kittredge and Mark Wall of Marshall Space Flight Center, as well as Joe Gasbarre and Tory Scola of NASA Langley, for help in developing the ground-based modeling techniques
- Frank Leahy was invaluable in determination of external natural environments
- USS portion of the model was originally built by Josh Giegel, and modified by Marcus Studmire, Jim Yuko, Bob Christie and Jim Myers (NASA GRC)
- RoCS submodels were supplied by Preston Beatty (TBE)
- Avionics submodels were supplied by Gary Holmstead (LMCO)
- The expertise of MSFC personnel in supplying aeroheating (Mark D'Agostino, Craig Schmitz, Jason Mishtawy, and Colin Brooks) is gratefully acknowledged
- The technical support from the team at Cullimore & Ring was outstanding
- The assistance of Tory Scola and Joe Del Corso at NASA LaRC in development of the BPMapper & Map2CFD codes is gratefully acknowledged

Thermal Backup Slides

Day of Flight - Thermal Event Timeline

Time (GMT)	Time (EDT)	Component activation
8:00	4:00	FTINU, MDU, RDU, URCU
8:20	4:20	ECS off (both FS and USS)
8:52	4:52	RRGUs on
9:30	5:30	ATVC, SIGI, APUC low power
9:30	5:30	All FSAM fans on
9:30	5:30	All USS fans on
9:36	5:36	All DAUs, MUX, MARM, cameras, VPDUs on for checkout
9:42	5:42	FTS activation
10:20	6:20	All DAUs, MUX, MARM, cameras, VPDUs off
11:34	7:34	All DAUs, MUX, MARM, cameras, VPDUs back on for launch
11:28	7:28	S-band and video transmitters on
15:27	11:27	All fans off
	11:28	MVBs start dissipating maximum power
15:29.30	11:29.30	APUC full power
15:30	11:30	Liftoff

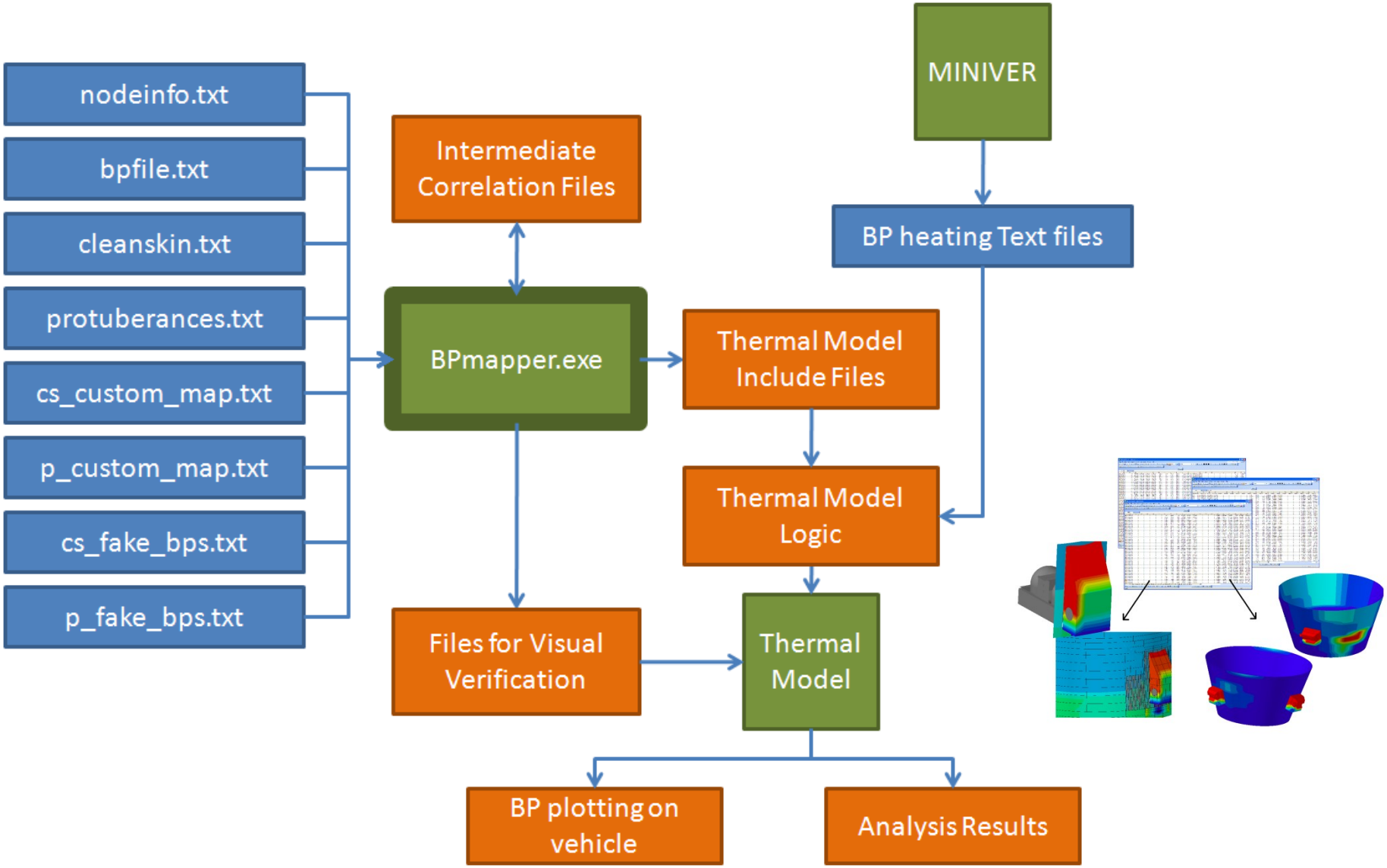
BPMapper Heritage

- Program called “renode” was first developed by a co-op at GRC (Josh Giegel) to automate node-BP mapping and include file generation for Ares I-X
- “BPMapper” was developed at Langley as a complete re-write of “renode” in order to:
  - Organize and correct code
  - Add customizability
  - Add additional mapping capabilities
  - Support visual verification of BP mapping and aeroheating
- First automated import from MINIVER to TD
- Latest 5.3 version updates:
  - All graphical (GUI) interface
  - Single external array file, faster run time x10
  - Graphical display of cold wall heating
  - No model node number restrictions

Previous Process

- Process was originally done manually
  - Huge amount of time spent on manual identification of closest node
  - Huge potential for errors, both in mapping and in text MINIVER files
  - No graphical verification of mapping or aeroheating
  - Large amount of time spent recovering from changes in provided MINIVER file format
  - High incentive not to update model or BPs, since that would force manual work in re-mapping

How BPMapper Works



BPMapper: Impact to Ares I-X Thermal Group

- High spatial fidelity of BP mapping to thermal model
- Visual verification ability
  - Identified huge errors in BP heating files that would have been missed
- Accurate, fast, customizable mapping
  - Allows increase in BP spatial fidelity by creating BP copies
- Fast/simple re-mapping whenever:
  - BP coordinates/numbers change
  - Node coordinates/numbers change
  - Nodes or BPs added
- Made full vehicle thermal analysis results possible for PDR/CDR